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Title: Remote Detection of Radioactive Materials Using Long Wavelength Infrared Laser Driven Avalanche Breakdown

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Proposal 310036
Remote Detection of Radioactive Materials Using Long Wavelength Infrared Laser Driven Avalanche Breakdown

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Funding: Received

National Nuclear Security Administration

24th Annual
Accelerator Test Facility (ATF) Users' Meeting
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Experiment Goals

- Year 1: Perform proof-of-concept scaling experiments for detection of radioactive materials at 10m standoff distance.
  - Characterize avalanche breakdowns with the 9.2μm long pulse beam line.
  - Optimize diagnostics
  - Test Po-210 (5.4MeV α), Fe-55 (6keV γ), and Cs-137 (662keV γ)
- Years 2-3: Extend technique to 30m detection distance.
  - Characterize effect of long propagation paths on sensitivity
  - Improve diagnostic sensitivity and resolution
  - Characterize effects of turbulence and aerosols

Background: Short Pulse IR Avalanche Breakdowns

- Avalanche breakdowns are ***local***
  - Centered around ***seed electrons***
  - Bounded by ***diffusion*** during pulse
- ***Discrete*** plasma “bubbles”
  - **Discontinuous** plasma density
  - Each blob has its own ***plasma density*** surrounded by neutrals

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What if?

- Short λ
  - Enough ***unwanted*** MPI seed electrons that their separation is smaller than the diffusion length
- Long τ_p
  - Enough time that the diffusion length is greater than the seed separation.

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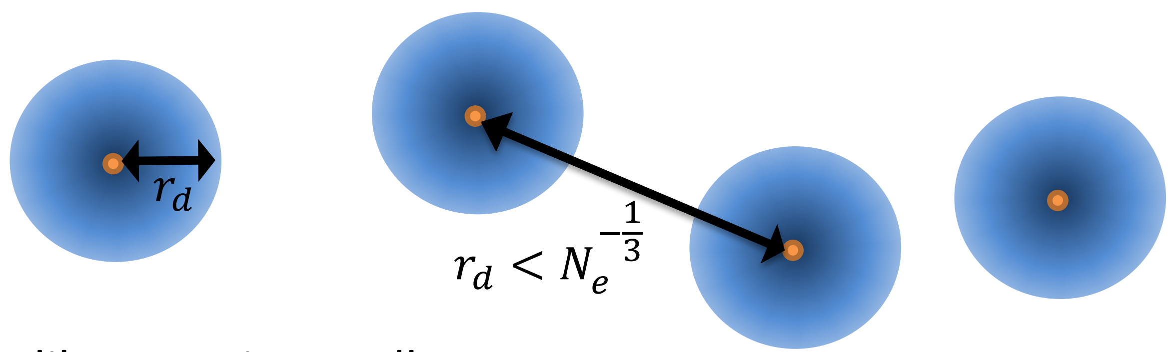
Discrete model necessary for:

- $\lambda > 2\mu m$
- $\tau_p < 1ns$

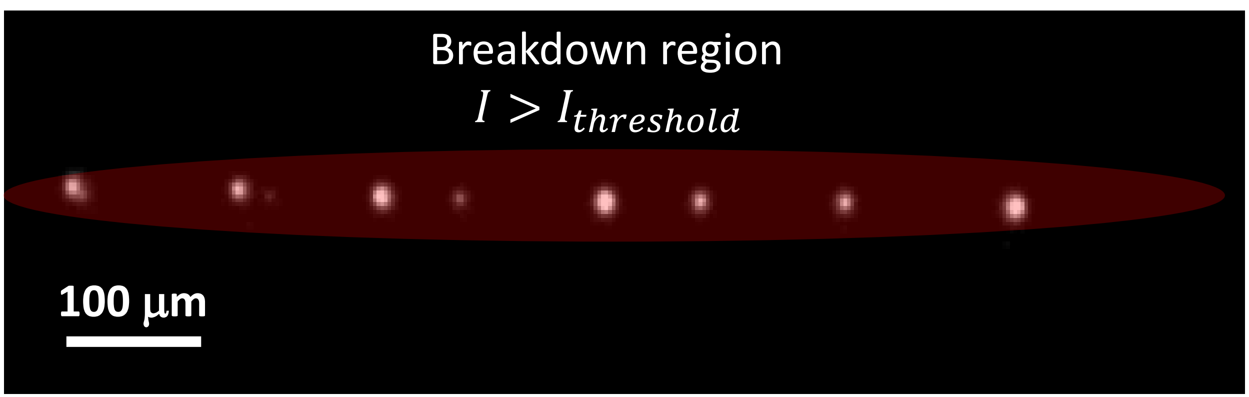
Low seed density

Electron motion is limited by diffusion, leading to discrete countable sites

$$r_d \sim \sqrt{2k_B T/m\nu_{en}} = \approx 0.3\sqrt{\tau[\mathrm{ps}]\, T_e\,[\mathrm{eV}])}\ \mu\mathrm{m}$$



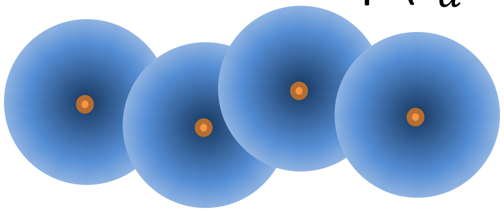
What this looks like experimentally:



Background: Avalanche as Plasma Diagnostic

High seed density

Once seed electrons are close enough that individual sites overlap ($r_d \sim N_e^{-\frac{1}{3}}$), breakdowns are no longer countable



For moderate densities, more seeds means higher chance that a seed will be near the laser focus, where intensities are higher, and breakdowns are driven faster. Statistics on breakdown timing measures seed density.

For very high densities, back to classic model of an exponentially growing plasma. Higher initial seed densities mean fewer doubling periods to reach a measurable plasma density.

Background: Modeling

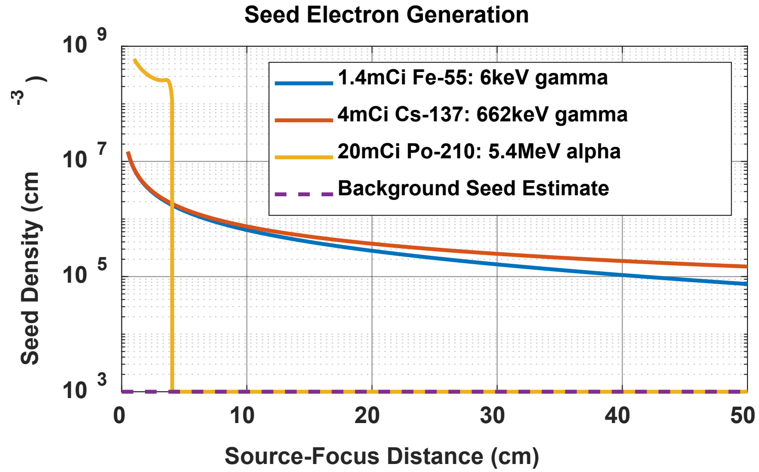
- Radioactive materials deposit energy in air creating an enhanced population of seed electrons

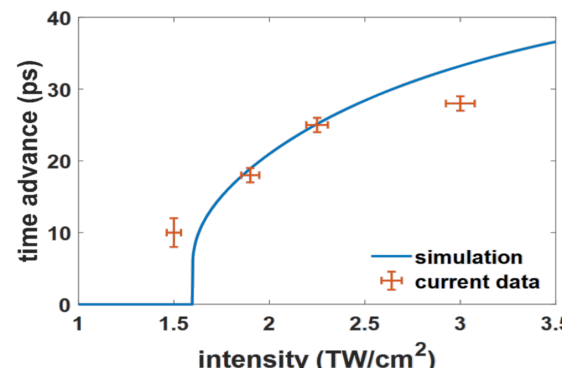
- Our model includes energy deposition, air ion formation rates, collisional energy transfer, and loss rates to calculate a steady-state seed density for air in the presence of a radioactive source

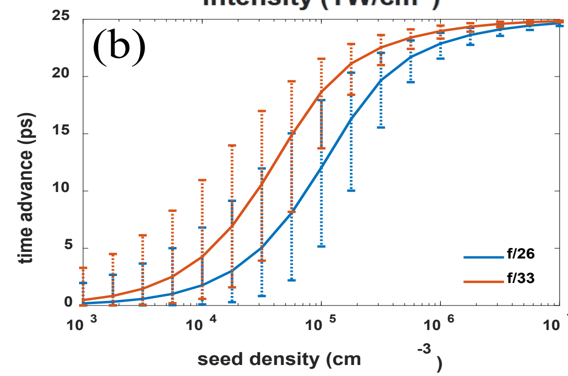
- We then add laser heating to model avalanche ionization

- Simulations for fixed intensity reproduces time advance results reasonably well

- Modeling random placement of charges in volume gives statistical spread of timing

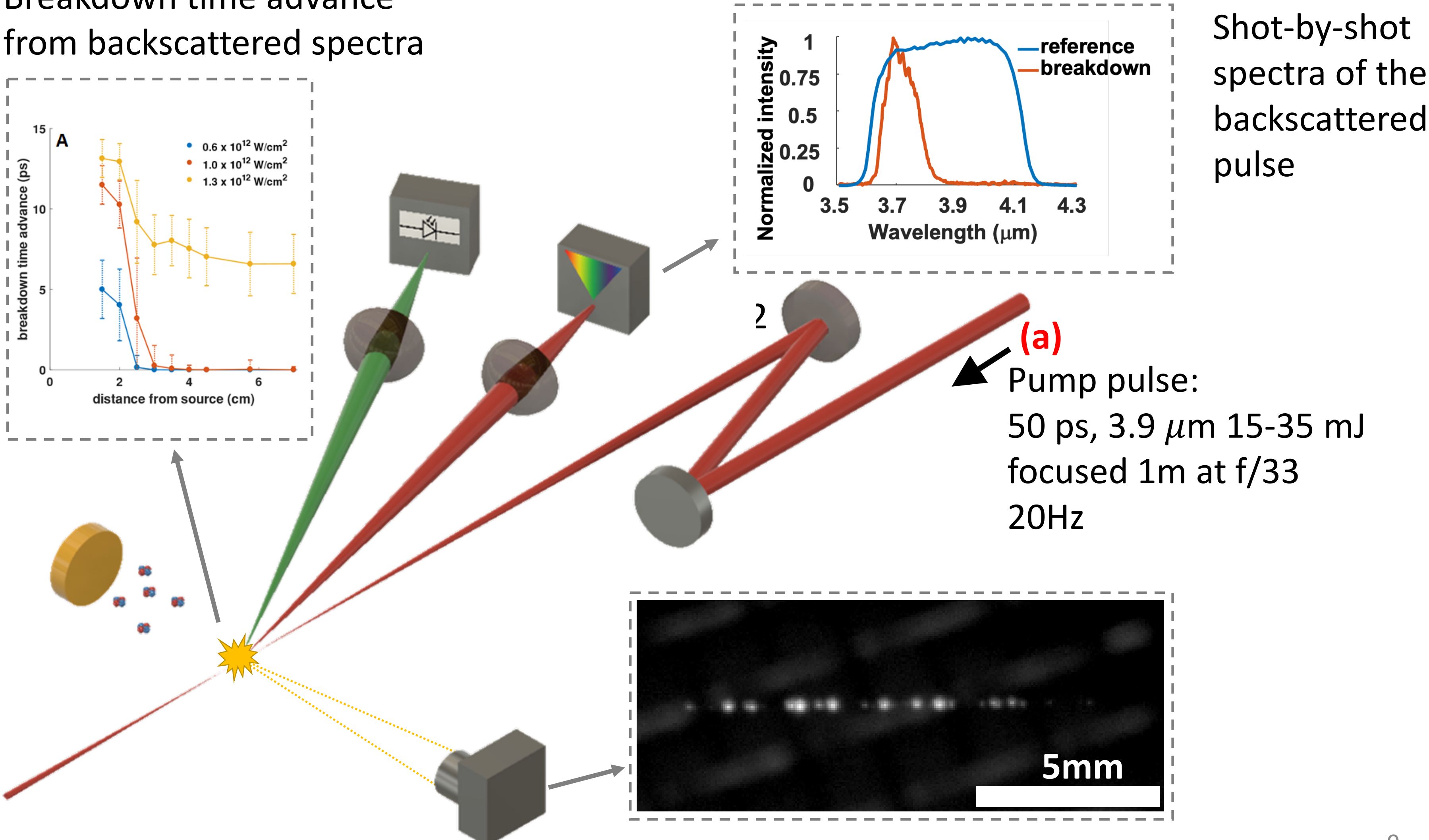






Background: Proof-of-Concept Experiments

Breakdown time advance from backscattered spectra

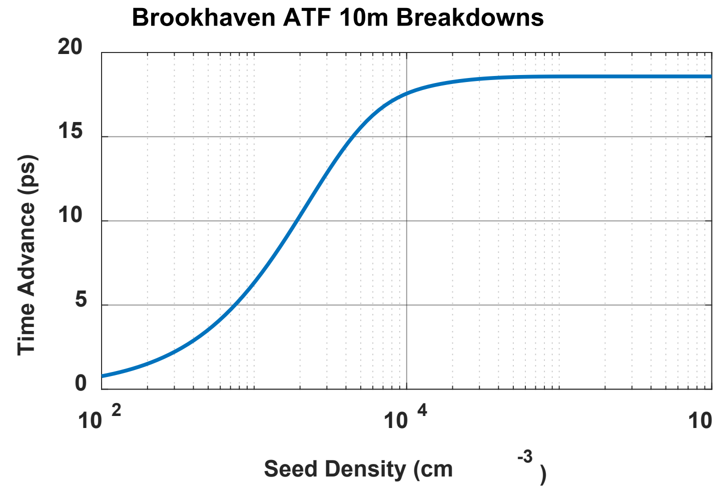


R. M. Schwartz, D. Woodbury, J. Isaacs, P. Sprangle, and H. M. Milchberg, Sci. Adv. **5**, eaav6804 (2019)
D. Woodbury R. M. Schwartz, and H. M. Milchberg, Optica **6** (6) (2019)

Experiment Layout

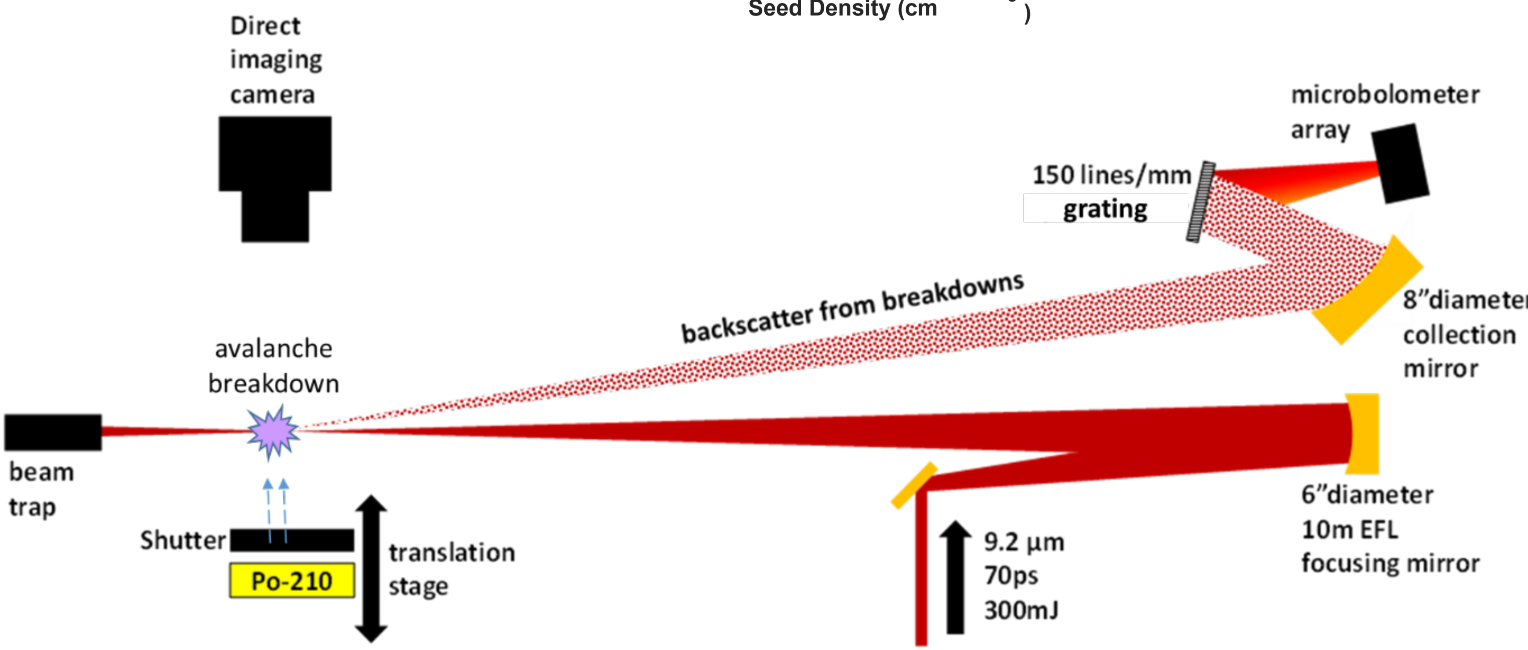
Video of breakdowns driven at 3.9μm.

Each spot is a breakdown seeded by a single electron.



Expected time advance for breakdowns driven by the uncompressed ATF beam line.

Sensitivity can be shifted with intensity and focusing geometry.



Experiment Schedule

Experiment	Goals/milestones
Year 1 **Demonstrate detection of radioactive material at ~10 m range (2-3 weeks)**	• Optics setup for 10 m range experiments • Determine breakdown threshold and background seed density in the absence of a radioactive source (this can be done with direct imaging of breakdown sites) • Calibrate and optimize the backscatter spectrum diagnostic • Demonstrate on/off detection using shuttered Po-210 alpha source • Measure seed density as a function of source distance and validate models • Repeat experiments with Fe-55 and Cs-137 x-ray/gamma sources
Year 2 **Demonstrate detection of radioactive material at ~30 m range (2-3 weeks)**	• Optics setup for 30 m range experiments • Same technical goals as above • Characterize effects of turbulence and aerosols on long propagation paths

Publications

1. R. M. Schwartz, D. Woodbury, J. Isaacs, P. Sprangle, and H. M. Milchberg, "Remote detection of radioactive material using mid-IR laser-driven electron avalanche," Sci. Adv. **5**, eaav6804 (2019).
2. D. Woodbury R. M. Schwartz, and H. M. Milchberg, "Measurement of ultralow radiation-induced charge densities using picosecond mid-IR laser-induced breakdown," Optica **6** (6) (2019).
3. D. Woodbury R. M. Schwartz, E. Rockafellow, J. K. Wahlstrand, and H. M. Milchberg, "Absolute Measurement of Laser Ionization Yield in Atmospheric Pressure Range Gases over 14 Decades," Phys. Rev. Lett. **124,** 013201 (2019).
4. R. Lakis, J. Sears, A Favalli, T. Stockman "Concept of Operations for Mid-IR Laser Driven Ion Detection," LA-UR-21-21282.
5. D. Woodbury, A. Goffin, R. M. Schwartz, J. Isaacs, and H. M. Milchberg, "Self-Guiding of Long-Wave Infrared Laser Pulses Mediated by Avalanche Ionization," Phys. Rev. Lett. **125,** 133201 (2020).

Electron Beam Requirements

Parameter	Units	Typical Values	Comments	Requested Values
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*	-
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	-
Compression	fs	Down to 100 fs (up to 1 kA peak current)	*A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*	-
Transverse size at IP (σ)	μm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	-
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	-
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	-
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	-

CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	µm	9.2	**Possible usage for alignment**	**-**
	Peak Power	GW	~3		**-**
	Pulse Mode	---	Single		**-**
	Pulse Length	ps	2		**-**
	Pulse Energy	mJ	6		**-**
	M^2	---	~1.5		**-**
	Repetition Rate	Hz	1.5		**-**
	Polarization	---	Linear		**-**
CO_2 CPA Beam	Wavelength	µm	9.2		**9.2**
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	2		**~10GW**
	Pulse Mode	---	Single		**Single**
	Pulse Length	ps	2		**70ps**
	Pulse Energy	J	~5		**~500mJ**
	M^2	---	~2		**~2**
	Repetition Rate	Hz	0.05		**0.05Hz**
	Polarization		Linear		**Linear**

Other Experimental Laser Requirements

Ti:Sapphire Laser System	Units	Stage I Values	Stage II Values	Comments	Requested Values
Central Wavelength	nm	800	800	*Stage I parameters are presently available and setup to deliver Stage II parameters should be complete during FY22*	-
FWHM Bandwidth	nm	20	13		-
Compressed FWHM Pulse Width	fs	<50	<75	*Transport of compressed pulses will initially include a very limited number of experimental interaction points. Please consult with the ATF Team if you need this capability.*	-
Chirped FWHM Pulse Width	ps	≥50	≥50		-
Chirped Energy	mJ	10	200		-
Compressed Energy	mJ	7	100		-
Energy to Experiments	mJ	>4.9	>80		-
Power to Experiments	GW	>98	>1067		-

Nd:YAG Laser System	Units	Typical Values	Comments	Requested Values
Wavelength	nm	1064	*Single pulse*	-
Energy	mJ	5		-
Pulse Width	ps	14		-
Wavelength	nm	532	*Frequency doubled*	-
Energy	mJ	0.5		-
Pulse Width	ps	10		-

Special Equipment Requirements and Hazards

- Electron Beam
  - N/A
- CO_2 Laser
  - Access to uncompressed (70ps) pulse with energies <5J.
- Ti:Sapphire and Nd:YAG Lasers
  - N/A
- Hazards & Special Installation Requirements
  - Geometry: Long, minimally obstructed laser beam path
  - Equipment: Routing and focusing optics
  - Hazards: Radioactive materials

Experimental Time Request

CY2022 Time Request

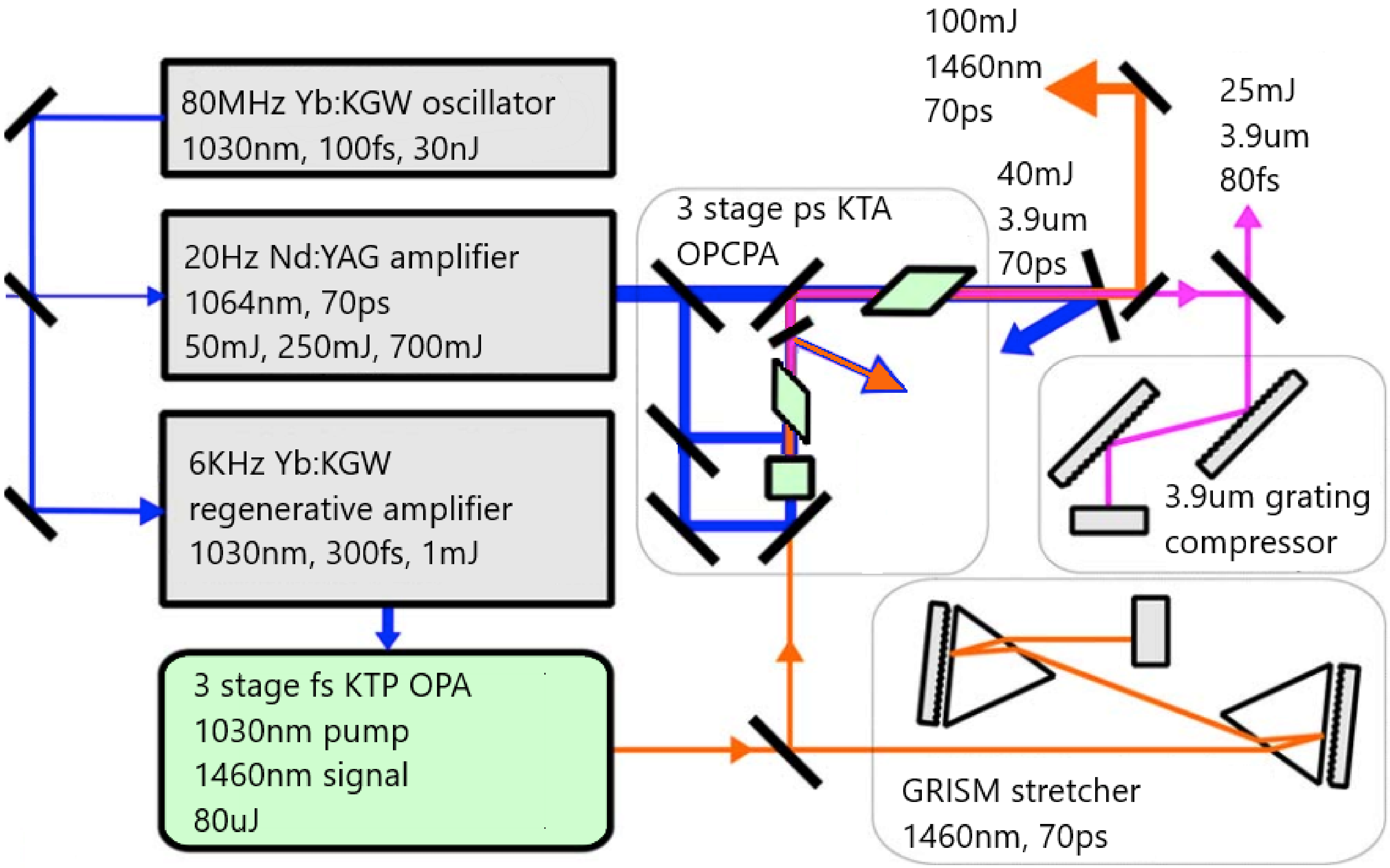
Capability	Setup Hours	Running Hours
Electron Beam Only	-	-
Laser* Only (in Laser Areas)	**50**	**150**
Laser* + Electron Beam	-	-

Time Estimate for Full 3-year Experiment (including CY2022)

Capability	Setup Hours	Running Hours
Electron Beam Only	-	-
Laser* Only (in Laser Areas)	**150**	**450**
Laser* + Electron Beam	-	-

* Laser = Near-IR or LWIR (CO_2) Laser

UMD 3.9μm OPCPA

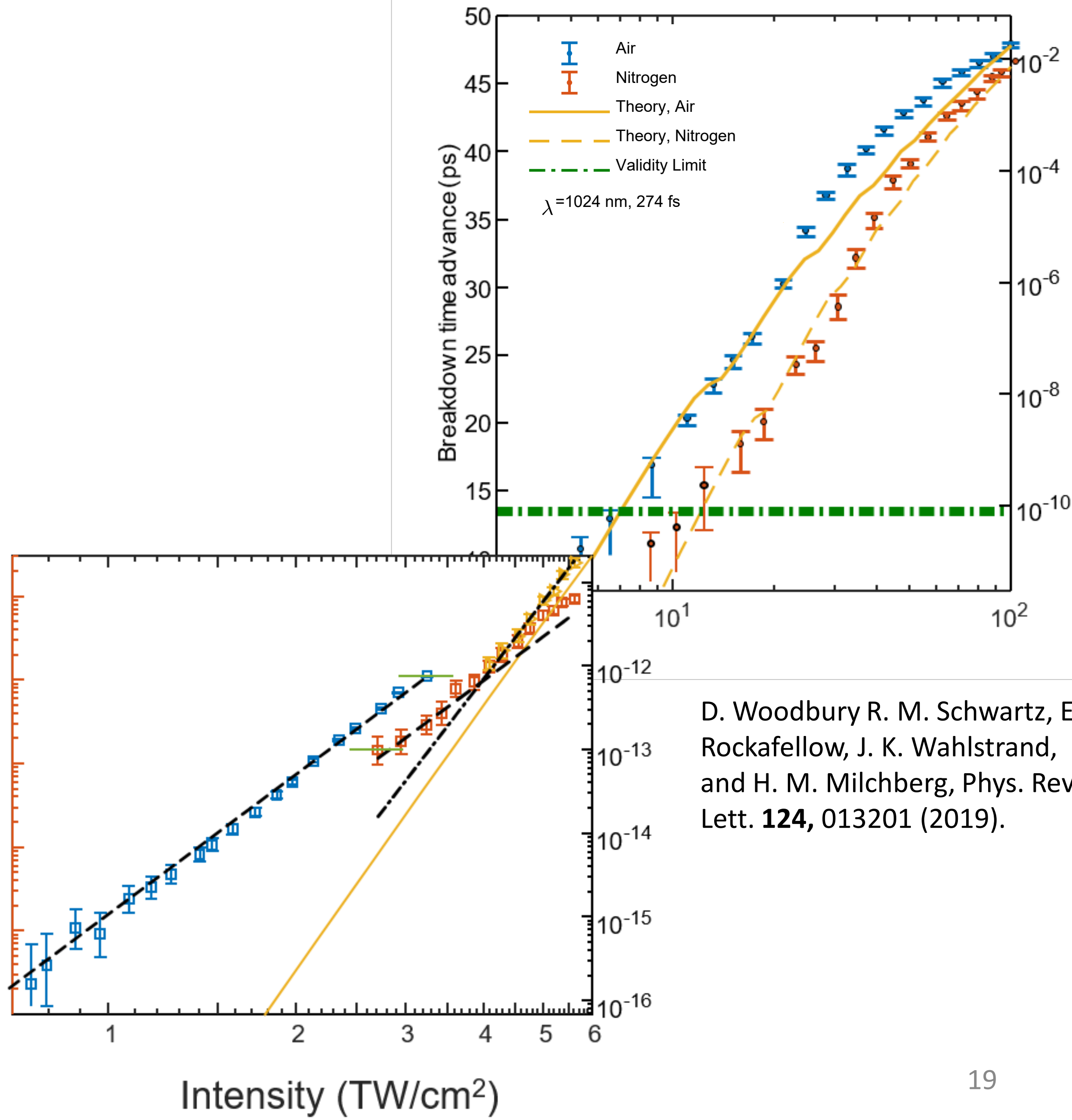


- 25 mJ, ~80 fs, λ=3.9 μm pulses, 0.3 TW
- Bypassing compressor produces **chirped 70 ps** pulses

(adapted from G. Andriukaitis *et al.*, *Optics Lett.* **36**, 2755 (2011))

MPI measurements

- Ionization yields at 1µm and 3.9µm have been measured at significantly lower intensities and at atmospheric pressure.
- Good match to tunneling model
  - Presence of ~6eV contaminant was universally seen at ~10^{10}/cm^3
- Combined dynamic range of ***14*** orders of magnitude in ionization yield
  - 10^3 to 10^{17} cm^{-3} electron density



D. Woodbury R. M. Schwartz, E. Rockafellow, J. K. Wahlstrand, and H. M. Milchberg, Phys. Rev. Lett. **124,** 013201 (2019).

Radiation + Avalanche Model

$$\frac{\partial n_e}{\partial t} = \frac{1}{E_{ion}} Q_{rad} + \nu_{photo} n_- + \nu_{coll} n_e - \nu_a n_e - \beta_{e+} n_e n_+ + \beta_n n_n n_-$$

$$\frac{\partial n_-}{\partial t} = -\nu_{photo} n_- + \nu_a n_e + \beta_{\pm} n_+ n_- - \beta_n n_n n_-$$

$$\frac{3}{2}\frac{\partial (n_e T_e)}{\partial t} = \langle \mathbf{J} \cdot \mathbf{E} \rangle - n_e \varepsilon_{loss}$$

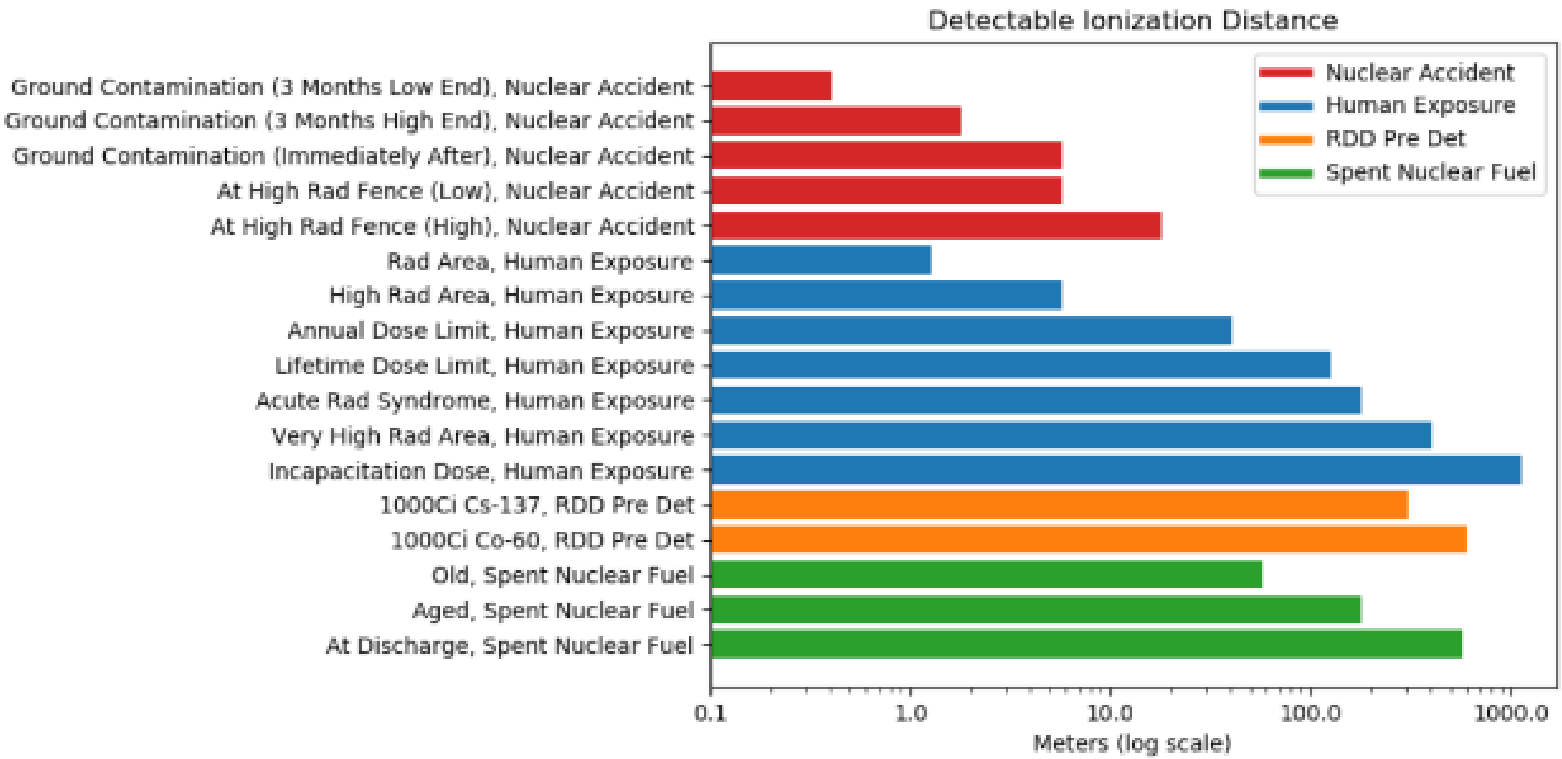
n_e: electron number density
E_{ion}: average ionization energy of air
ν_{photo}: photo-detachment rate
ν_{coll}: collisional ionization rate
ν_a: e + O_2 -> O_2^- attachment rate
β_{e+}: electron-ion dissociative recombination rate

β_n: negative ion detachment rate due to collisions with molecular nitrogen
$\beta_{\pm}$: ion-ion recombination rate
T_e: electron temperature
<**J**·**E**>: ohmic heating rate
ε_{loss}: electron energy loss rate in air

Note: almost all of these have temperature dependence!

J. Isaacs, “The physics of high-intensity laser-matter interactions and applications” Thesis (2019)

Detectable Sources



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